Towards an ontology driven approach for systems interoperability and energy management in the smart city

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***Abstract*— Modern Information and Communication Technologies are definitely a key factor to develop the green and sustainable applications that the so-called "smart city" needs. Effective management of resources, gathering and interpreting data as well as ecological considerations are prerequisites to turn such a vision into reality. The European FP7 project DIMMER address these issues by providing a flexible Internet of Thing platform for application development and data integration, exploiting information about buildings, energy distribution grids and user behaviors. Among those applications, the possibility to real-time access and aggregate information about building environmental characteristics and energy consumption enables the optimization of energy management and control, as well as the user's awareness about, which is the scope of the DIMMER project. The paper will describe the ontology-driven approach, as well as the actual design, exploited to model the physical world within the context of this project, adding a special emphasis on the state of art research in the field of energy profiling.**

Keywords—Dimmer; Smart City, Ontology; Energy profile; Internet of Things;

I. Introduction

Energy efficiency (term that includes consumption reduction as well as greener and minor production) is essential for economic, social, and environmental reasons: worldwide institutions, including European Union [1], clearly consider this as a primary objective. In the EU, this concern is expressed through the "20-20-20" targets, which includes the 20% improvement in the EU's energy efficiency. One of the most relevant initiatives to achieve this objective is the 2012 "*Energy Efficiency Directive*" [2]. It includes several measures and policies trying to address different areas and sectors of energy consumption, including energy management in the future European smart cities. "Buildings", one of the greatest energy consumers, accounting for the 30% of the overall energy consumption in EU, was included in 2012 directive, which requires EU countries to establish national plans for renovating the whole building stock. The Energy Performance of Buildings Directive (EPBD) [16] obligates Member States to establish minimum energy performance requirements for all buildings, to reach by 2020 the nearly zero-energy building objective.

In such scenario, ICTs are key players: pervasive sensors and actuators can efficiently control the whole energy chain (Smart Thermal/Electricity Grid) [31], and various information about heating/cooling and electricity grid can be accessed and integrated. Those information, coming from multiple and heterogeneous sources, can be managed together through ICT technologies (that can be considered COTS) within a sort of centralized decision system [32] operating at district level. To unlock the potentiality of these technologies, the DIMMER project [3], in the scope of this paper, focuses on the interoperability of district energy production/consumption (including environmental conditions and user data).

The DIMMER system interfaces with building information and district energy distribution networks models, integrating them with real-time data from pervasive sensors at grid and building level, allowing information access and visualization through Web Services generated using an ontology-based approach.

This paper will briefly introduce, in section II, the DIMMER project context, expectations and developments, focusing on the analysis of the energy profile ontology based modeling in section III. Section IV provides an overview of the DIMMER ontology, while the energy awareness framework and the Web Portal for energy optimization are analyzed in sections V and VI. Finally, authors' conclusions are reported in section VII.

II. THE DIMMER PROJECT

The DIMMER project aims at developing a distributed software infrastructure to create a virtual District Information Model (DIM) and simulation framework. Such platform enables the interoperability across heterogeneous technologies, either hardware and software, that can collect, process, and visualize district-level energy usage and the structural parameters of buildings and energy distribution systems. Figure 1 shows the architectural schema of DIMMER platform. It is a three-layered distributed architecture with: i) *Data-source Integration Layer*; ii) *District Services Layer*; iii) *Application Layer*. The DIMMER platform exploit middleware technologies to build the DIM by correlating information about: i) BIM (Building Information Modeling), a 3D parametric model for each building in the district; ii) SIM (System Information Model) that represents the models of energy distribution networks; and iii) GIS (Geographic Information System), that provides geo-referenced information about different entities in the district. In addition, this platform collects (near-) real-time monitoring information sent by IoT (Internet-of-Things) devices: a set of heterogeneous sensors installed in buildings and along distribution networks, with the scope of enriching the DIM with concrete energy-related data. Such heterogeneous data-sources represent the *Data-source Integration Layer.*

The *District Services Layer* is the core of the platform, composed by middleware-based components providing services at district level. *Service Catalog* and *Resource Catalog* provide indexes of all available services and IoT resources. *Message Broker* provides asynchronous communications exploiting the publish/subscribe approach to share data. The *Historical data-storage* collects data sent by devices deployed: it has been designed to integrate already existing databases owned by other actors. The *Semantic Metastore* provides information about the DIMMER ontology (see Section IV). The *Energy Efficient Engine* simulate new control policies for optimal demand response and energy distribution at district level. Such control policies can be designed and deployed on the top of finer real-time energy and environmental information collection. Hence, it exploits data from devices in the district correlated with DIM information. Analysis outputs can be used to analyse energy related data and implement or assess different energy optimization strategies. Finally, the *Application Layer* provides client applications to: i) Visualize in real-time energy related information in the building and district environment; ii) Correlate user profiling and feedback information with building/district utilization to energy distribution optimization; iii) Compare energy situations and measures from different monitored and controlled facilities/buildings; iv) Perform cost analysis to evaluate the economic impacts of such optimized policies and enable the offer of personalized tariff plans on the basis of energy profiles. This will represent a new instrument that will also make the user more conscious about economic implications of their actions and of possible trader migration.

In a nutshell, the DIMMER project aims at building a distributed, smart digital archive of a city-district, in which different actors in the smart city scenario can publish and use different information to provide innovative services. Three categories of end users of DIMMER has been considered: i) Public administrators, having energy consumption/expenses reduction tasks; ii) Building managers, in charge of to guarantee and improve building(s) operability according to intended use; iii) Energy utilities professionals, which manage the more efficiently and effectively possible energy production and/or distribution.

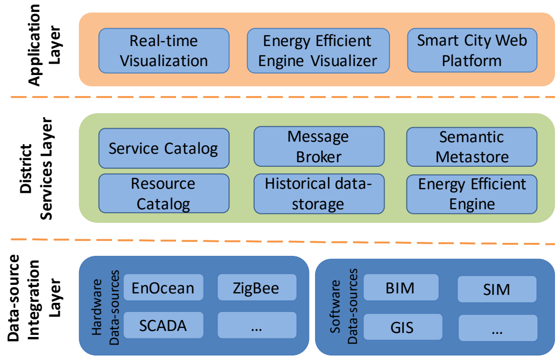

Figure 1. Architectural schema of DIMMER Platform

In order to validate this platform, prototype installations and validation is performing in two different cities: Manchester (UK) and Turin (IT). In these cities, mixed-use urban districts have been considered where both public and private buildings are located. As buildings consume the most energy during the operational stage of their life cycle (~80%), DIMMER has given special attention to existing and historical buildings. The expected results are reductions in both energy consumptions and CO_2 emissions by enabling more efficient energy (electrical and thermal) distribution policies, accounting the real characteristics of district buildings [33].

III. ENERGY PROFILES ONTOLOGY-BASED MODELLING

Energy performance assessment and representation demands for models able to deal with an increasing variety of ground truth data, generated through heterogeneous monitoring networks and devices. The emergence of IoT (Internet of Things) approaches to smart cities is stressing the importance of a uniform, machine understandable, representation of the energy qualities of devices, rooms, buildings and by extension of districts and cities. This need is currently acknowledged by several research efforts, both industrial and academic, which aim at building domain ontologies that model energy consumption and performance.

Similarly to what happens in other domains, in energy modelling ontologies are preferred over other representations for their ability to formally - they are based on Description Logic (DL) and its derivatives - represent a domain of knowledge, while preserving a readable representation, which enables humans to easily grasp represented concepts and relations. Moreover, by being based on logic, ontologies allow for model consistency checking and automatic inference that might unveil implicit information hidden in the domain representation. Finally, thanks to the Linked Open Data initiative [28], ontologies can be aligned and/or linked quite naturally, thus offering means to interoperate between formats and between communities of interest, easily.

In the energy domain, ontologies are employed to define shared and common inter-lingua for aspects involved in performance evaluation, energy rating, device consumption profiling, etc. Approaches in literature, typically address the energy domain by splitting the analysis along different forms of energy, mainly electrical and thermal. This on one hand, permits to tackle the specificities of the single energy form and related engineering domains, but on the other hand prevents a structured and comprehensive approach to energy representation, at higher levels of detail, e.g., at the district level.

The DIMMER project aims at establishing a sound liaison between domain specific models in the energy representation field, with the goal of enabling better representation and analysis of energy qualities at the building / district levels, regardless of the particular form of consumed energy. To reach such a goal the project conducted a reasoned analysis of existing models in the energy domain, for both electrical and thermal forms, which is summarized in this section. For each model, a short overview is provided highlighting the strength of the approach and the links with other similar models. Cross-linking between electrical and thermal representation is emphasized, where possible.

A. Electrical sub-domain

Electric energy consumption is one of the most important aspects modelled in the smart home domain. Such an importance is related to the amount of "saving" that can be achieved by considering energy management as fundamental part of home automation. Approaches for modelling energy consumption in smart environments mainly address the problem under two complimentary standpoints. The first aims at modelling instantaneous consumption, i.e., consumption levels associated to specific, observable states of devices and appliances. The second, instead, considers the overall consumption "profile" of a given electric device, i.e., the sequence of consumption levels associated to a complete "working" cycle. Consider, for example, a washing machine. The first approach finely models the machine consumption when spinning, heating water, drying clothes and, infers the current consumption depending on the machine state. The second, instead, considers complete washing cycles, e.g., delicate washing, and models the energy consumption trend with respect to time, often in discrete steps.

PowerOnt [20] follows the first approach and provides a lightweight ontology that models consumption associated to specific states of electric devices. A rather coarse, yet modular, approach is used defining three levels of consumption for each state, with increasing level of detail. States are associated with a typical consumption (in W) which is derived from catalogues of device categories, e.g., A class fridges. Such a typical consumption can be better specified if the nominal consumption rate is available for the specific state. Finally, the model provides means to model actual consumption of the device, in a given state, extracted through direct metering. No notion of time is included in the model, and no direct/explicit support to thermal energy is provided. However, the model is general enough to represent both thermal and electric energy, with little extensions.

The challenge of representing electric device consumption has been tackled in several initiatives driven by home-automation standardization bodies. Among the others, the Energy@Home consortium [37], which was involved in the definition of the ZigBee Smart Energy [30] and Home Automation [29] specifications, tackled energy consumption modelling in terms of energy profiles, i.e. of sequences of consumption levels, which evolve in time depending on the device type / operating cycle. Unfortunately, such profiles have not been formalized in terms of ontologies and they have only been modelled in terms of datatypes associated to specific ZigBee Clusters.

In the last years, the increasing need for standardization of energy consumption modelling, and representation, promoted the European initiative on Energy Using and Producing Products [21], which lead to the creation of the Smart Appliances Reference ontology (SAREF [35], [36]), now an ETSI standard [22]. SAREF formalizes in OWL the "energy profile" concept developed in the ZigBee alliance, thus providing a standard, machine understandable representation of energy consumption of devices, over time. Moreover, it models explicitly the observable states of devices (as its device modelling approach partly stems from the earlier DogOnt ontology [18]) and is therefore directly linkable with PowerOnt. This offers a complete modelling of both instantaneous and temporal energy consumption. It must be noted that, although SAREF implicitly assumes that devices are "electrical" and that the associated consumption is related to the "electricity" form of energy, no formal constraints prevent modelling primitives to be exploited for representing thermal quantities. As such, SAREF can be considered a nice merger for the two domains.

While SAREF tackles energy consumption modelling at the device level, ThinkHome (also exploiting many of the DogOnt concepts for device modelling) [23] addresses energy representation with a more structured approach. In fact, it also considers building information for supporting optimized control strategies striving for energy-efficient operation of smart homes and buildings. This goal is achieved by explicitly integrating data stored in Building Information Models (BIM). Both Industry Foundation Classes (IFC) concepts and Green Building XML specifications [24] are supported. The common modelling base shared by SAREF, PowerOnt and ThinkHome, provides a strong hint on the viability of a unified energy-modelling framework, based on ontologies, able to deal with different levels of detail from single devices to full homes and buildings, regardless of the energy form. The latter aspect, which is worth citing in the electrical domain, regards consumption flexibility, i.e., the ability to perform temporal load switches depending on both internal (self-production) or external (active demand-response) constraints. In such a context, some attempts can be cited which tackle the flexibility challenge by exploiting formal, ontology-based modelling. Among them, the MIRABEL project defined the FlexOffer ontology [25] representing objects involved in energy flexibility systems and their relationships. It provides a conceptual framework where the flexibility concept is defined and set in relation with building information and smart grid data. FlexOffer is mainly intended as a tool supporting IT and Energy stakeholders to handle supply and demand of energy, using a common interoperation language. In addition, FlexOffer is partly integrated in SAREF.

B. Thermal sub-domain

Ontologies addressing energy profiling under the thermal standpoint typically represent the temporal evolution of consumption, as instantaneous data is less relevant in environments where time constants are of the order of minutes or hours. In the thermal domain, most of the ontology-based models address energy performance evaluation in terms of multiple energy efficiency indexes, as prescribed by the EPBD, which imposes the adoption of measures for improving energy efficiency in buildings.

The Energy Efficiency Ontology (EEOnt) [17], for example, provides a semantics-rich, representation of energy data in terms of EPBD objectives, offering means to model buildings and energy efficiency in a unified way. It, moreover, provides tools for building energy assessment inventories, thus enabling the creation of formal, machine understandable and easily assessable certification schemes. EEOnt builds upon the work done in DogOnt [18] and its extensions. Through DogOnt, appliance properties are exposed according to existing semantic models, while power consumption is modeled by introducing a specific Energy Profile [20] ontology. EEOnt explicitly represents links between building components and corresponding energy efficiency indexes, which is clearly complimentary to the ThinkHome approach.

The SmartCoDE ontology model [15], instead, represents the thermal homologous of profile-based modeling of electric consumption. It provides a classification of Energy using Products (EuPs) into seven categories based on their compound temporal and energy behavior. Included categories are namely: (a) variable services; (b) thermal services, (c) schedulable services, (d) event-timeout services, (e) charge control, (f) complete control, and (g) custom control. Moreover, an energy management and a cost profile characterize each product. SmartCoDe mappings with SAREF exists and can be easily obtained as reported in [26].

C. City and district-level modeling

Systemic views of energy consumption are nowadays gaining momentum, thanks to an increasing demand for representing building energy profiles in the context of a wider district- or city-level vision. The Urban Energy Ontology (UEO) [10], elaborated in the SEMANCO project [11], among many similar initiatives, describes the domain of urban planning based on the SUMO upper-level ontology [12]. It includes concepts derived from diverse sources and, related to the domain of urban planning and energy management. UEO encompasses terms and attributes describing regions, cities, district and buildings, energy consumption profiles and CO2 emission indicators, together with climate and socio-economic factors that influence energy consumption.

The CERISE CIM Profile for Smart Grids, i.e., the Common Information Model developed by the Cerise-SG project [13], addresses interoperability of information exchanged between smart grids, public authorities and geographical information. The Cerise-SG project, in particular developed semantic model transformation services bridging the gaps between modeling domains relevant to smart grids (e.g., as in [27]), and providing alignment and conflict resolution facilities. The Energy in Buildings Ontology [14] is another attempt to provide a systematic framework for city-level energy modeling. It provides a reference model for publishing energy performance data of public buildings in Italy, with a Linked Open Data approach. With respect to the previous models, and in addition to building-level representations, it addresses and represents energy flows incoming and outgoing from a building district.

D. Discussion

Given this rough survey of current energy modeling efforts, it clearly emerges that energy consumption modelling at district and city level is feasible, and can be achieved on the basis of a solid, standard and shared modeling framework based on ontologies. Among analyzed efforts, SAREF offers the baseline model for high granularity information on device states, which can be easily related to both instantaneous (PowerOnt) and temporal (SAREF itself) behaviors in terms of energy. Thanks to ThinkHome and EEOnt, homes and buildings modeled using SAREF can be formally characterized in terms of energy efficiency indexes, with traceable relationships to building features modeled in BIM.

Ontologies providing district and city-level views of energy performance indicators and models for energy flows are available. The missing “last-mile” is explicitly linking the latter systematic representations with building-level characterization, in a possibly shared framework using SAREF as foundation. Moreover, the resulting modelling frameworks needs to explicitly address policy regulations for the energy market, as this aspect is crucial for the successful exploitation of ontology-based energy profiling. In this sense, cities are already moving towards policy-making based on data: an example is represented by the "Global City Indicators" ([6], [7]), a term created in 2010 to establish a global standard of over 100 city indicators with a standardized definition and methodology. Unfortunately, a formal representation of policies and regulations in the energy domain has yet to appear, and it can be considered as an open challenge that calls for suitable solutions to be designed and developed.

IV. THE DIMMER ONTOLOGY

Many context-modelling approaches are known in scientific literature. Strang [34] provides a list of different context modelling approaches: 1) Key-value models, 2) Markup scheme models, 3) Graphical models, 4) Object-oriented models, 5) Logic based models and 6) Ontology based models. Despite of advantages and disadvantages introduced by each approach, the goal of using common specification models and languages is to handle the acquisition, transmission and sharing of context. Different approaches affects to different context complexity: there is no “one solution” specification language, but modelling approaches can differ in terms of expressiveness, interoperability, efficiency, programming effort required, reasoning support provided, ambiguity and incompleteness information management. In DIMMER, addressing applications for energy optimization which are easy to be designed, as well as easy to be deployed (and enough effective to be rolled-out at room/building/district level) has been designed an ontology model describing functionalities, objects involved (like devices or infrastructures), people involved (users or group) and the run-time environment (physical parameters measured, boundary conditions). In addition, to reason about energy savings at both building and district level, it has modeled domain's physical objects (buildings, floors, elevators, stairs, rooms, office etc.). In addition, following the IoT-A reference architecture [5], objects (including sensors and/or actuators) were represented as "Virtual Entities", resources that can provide information about the real world context. Data used in the DIMMER applications come from existing systems using different schemas, which needs to be integrated within an exhaustive view of district energy production and consumption. Hence, the DIMMER Ontology consists of a set of interrelated models extending and referencing earlier work and well-known - previously established - vocabularies that provide a unified schema of the application domain.

The DIMMER Systems Integration Ontology (SIO) is an application ontology [8] that describes the Internet of Things and middleware resources. By mapping heterogeneous data models to a simplified common schema, it integrates data in Geographical Information Systems (GIS), Building Information Models (BIM) systems as well as historical and real-time data from Internet of Things devices and sensors. The ontology describes in which systems data (about a physical object in the domain) are stored and how to retrieve them. It is based on the SAREF and SEEMPubS ontology [33], which were developed to describe the sensors and data used to monitor indoor conditions and energy consumptions on a building level, in the smart appliances domain. In DIMMER, those ontologies have been extended for the use at district level, while the modeling of software services is re-using concepts from OpenGroup SOA Ontology [4]. Figure 2 provide a simplified excerpt of the DIMMER ontology, where unnamed arrows indicate subsumption relations. The activities defined also profiles and policies to classify devices from the energy point of view, in order to integrate them for thermic and electrical consumption optimization. Energy profiles and energy policies for the different sensors and devices were used in an integrated way, at both district and building level. A dedicated server for the Semantic Datastore has been provisioned and the Jena framework has been installed on this server. A specific use case in Energy efficiency and benchmarking has been selected to focus the ontology development work on. These results are integrated into the demonstrator in both Manchester and Turin.

V. PRELIMINARY RESULTS

In the area of ontology development, a list of relevant existing ontologies to re-use or specialize in DIMMER has been specified. An assessment framework for evaluation ontology storage and reasoning systems has been developed and used to select the Jena framework for use in DIMMER. A dedicated server for the Semantic Metastore has been provisioned and the Jena framework and Apache Jena Fuseki SPARQL Server have been installed on this server. To facilitate integration with the other DIMMER components, a layer on top of the Fuseki SPARQL server, which allows parametrized queries to be defined and called using HTTP protocol verbs, has been installed. The Semantic Metastore may thus be used without any need for knowledge of ontology query languages. A specific use case in Energy efficiency and benchmarking which supports the Energy Optimization Portal has been selected to focus the ontology development work on. The results at the time of writing are integrated into the demonstrator in both Manchester and Turin pilots. Through the DIMMER ontology, applications can combine services providing live measurements from sensors or historical sensor values with results from long-running simulation tasks in an Energy Efficiency Engine. Using simple HTTP calls, the Portal can find service providing data on districts and buildings for specific properties. A simplified example of a SPARQL query for virtual buildings that match the selected actual building with respect to a certain property is provided in Figure 3, which includes the HTTP call to access the query.

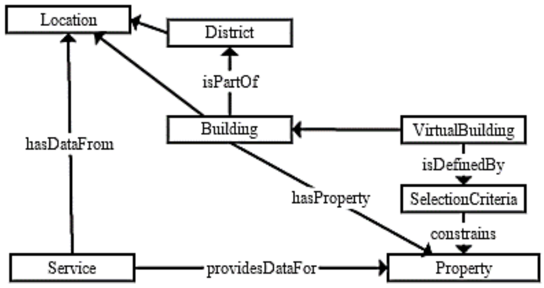

Figure 2. Simplified DIMMER application ontology

VI. ENERGY AWARENESS FRAMEWORK

The DIMMER architecture includes an intelligent Context Energy Awareness Service Framework, capable of managing sensor data and events across different contexts and situations. Such framework provides specific context aware services that offers ambient feedback on the energy status of public and private spaces and the situational context, aggregating and fusing data from different heterogeneous sub-systems and sensors spread into the environment. In the initial modelling stage, each service is equipped with a service specification derived from the ontological model of its context, which, in turn, are submitted as a Semantic Web standard for contextual modelling. The results of the analyses provide the basis for constructing a set of autonomous services, which require high-level platform and application independent interfaces to both sensors, sub-systems and underlying data warehouse and business intelligence systems. Based on context knowledge of sensors and sub-systems input, the services provide a broad ensemble to both energy awareness and energy control.

```
PREFIX dimmer: <http://www.dimmerproject.eu/#>
SELECT  ?virtualbuilding
WHERE   {
    ?building dimmer:hasId $buildingid .
    ?building dimmer:isPartOf ?district .
    ?virtualbuilding dimmer:isPartOf ?district .
    ?virtualbuilding dimmer:isDefinedBy ?criteria .
    ?criteria dimmer:constrains ?property .
    ?property dimmer:hasName "$property".
     FILTER (dimmer:isWithinConstraints(?building,?criteria))
        }
LIMIT $top OFFSET $skip

 curl -H "Accept: application/json"
https://metastore.dimmer.eu:8181/api/service/SparqlQuery/
urn:res:similarvirtualbuilding?
buildingid=UKD33-01&property=TotalEnergy&top=10
```

Figure 3. Example of SPARQL query

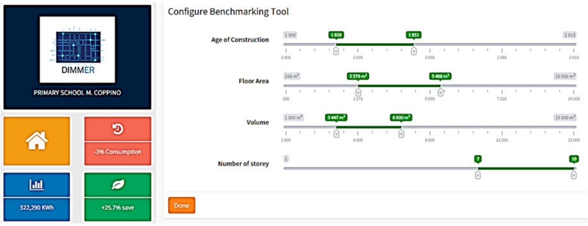

Figure 4. Benchmarking Tool Virtual Building configuration

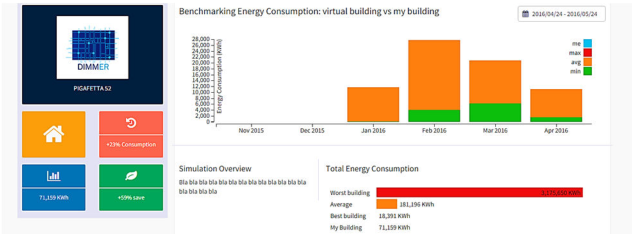

Figure 5. Consumption benchmarking: virtual building vs my building

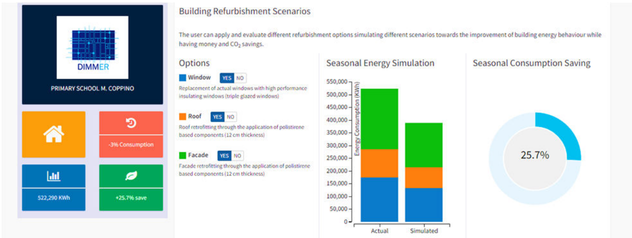

Figure 6. Building Refurbishment Scenarios

VII. Energy Optimization Portal

The Benchmarking tool is part of the web visualization tools developed in the framework of the DIMMER project that offers benchmarking capabilities by means of comparison energy situations in a district. The district and city-level views provided by the ontology system is the basis for the tool capability of evaluating how the district is influenced by the single building and vice versa. Another innovative aspect is provided also by the possibility to compare the building energy behavior (in terms of energy consumptions) against a "virtual building" representing the average behaviors of similar buildings in the district for privacy reasons. In the benchmarking tool, the concept of "district" besides being represented by spatial boundaries (e.g. all buildings of Turin) is extended with physical (e.g. all buildings with a specific floor area) and Virtual entities (e.g. all buildings with an energy consumption below a specific set point). The criteria definition for the Virtual Building identification affects the interaction with different dataset and domain: BIM, GIS and SIM. To this aim, the DIM context layer may perform aggregated queries to different data set. Figure 4 shows the configuration panel used to define the boundary condition of Virtual Building. Sliders helps users to define benchmark parameters. Each Virtual Building configuration is translated by the application in parameterized SPARQL query to retrieve data from the Semantic Metastore and Ontology service layer. The integrated interface of the Energy Optimization Portal allows the visualization of the "district level data" provided by the Benchmarking Tool. In particular, the user, according to the profiles rules, is able to exploit the functionalities of Benchmarking Tool and thus perform actions like: 1) view consumptions of the selected building in different periods; 2) edit parameters to define the Virtual Building to have comparisons against it (Figure 5); 3) see the consumptions of the selected building in a period compared to energy behavior of the Virtual one; 4) compare energy behavior of the selected building under current conditions with those simulated for the same selected building after improvements (e.g. façade/roof retrofitting, window replacements, upgrade of the heating supply system) in order to preliminary evaluate potential energy/economic savings (Figure 6).

VIII. Conclusions

This paper presented some of the results of the DIMMER project, giving the evidence that ontologies providing district and city-level models and views of energy performance indicators or energy flows can be integrated with context characterizations at building level. It has been described the rationale upon the integration of different ontology having the objective of enriching BIM and district level 3D models through real-time data from sensors, to analyze and correlate buildings utilization and provide real-time feedback about energy-related behaviors: this allows access and visualization of energy-related information for energy and cost-analysis, tariff planning and evaluation, failure identification, maintenance or other value added services. Indeed, policy makers will be able to relate different phenomena happening at the same time at district level, which are non-banally linkable otherwise: having that information at district level is incredibly telling for top-down action and effective sustainable planning.

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